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NEW DESIGN APPROACH FOR BASE-ISOLATION OF ESSENTIAL SANITARY FACILITIES IN HIGH-SEISMICITY ZONES OF COLOMBIA

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Abstract

Base isolation is one of the most innovative and successful solutions for seismic protection of building structures. In countries like Japan, China, Russia, Italy and USA, there are numerous isolated buildings. On the other hand, some Latin American countries (such as Chile, Colombia and Peru) have been making significant progress in the implementation of this technology, although the number of applications is still moderate. Colombia and Peru merely refer to US regulations, while Chile has its own seismic isolation code, although is strongly inspired by the US rules. Moreover, US guidelines are worldwide imitated in many other countries. Throughout the world it can be easily observed that seismic isolation is apparently less spread in countries where American regulations are considered. Therefore, the presumable excess of conservatism of such regulations might contribute to delay the worldwide development of base isolation. The objective of this paper is to analyze the design codes for base isolation of Japan, China, Italy, USA and Chile with the aim of comparing their requirements. The final goal is to investigate the need of developing regulations governing the application of this technology in Colombia. For this purpose, a sanitary prototype building located in a high seismicity zone of Colombia is analyzed as a case study. Initially, this building is designed as fixed-base according to Colombian design code; then the isolated building is re-designed according to the aforementioned considered regulations. Obtained results are compared and conclusions are issued.

Keywords: Pounding; RC buildings; Nonlinear Analysis

1. Introduction

Base (seismic) isolation consists in incorporating, between the building and the foundation, elements (commonly termed as isolators) which are highly flexible in the horizontal directions, although are rigid in vertical direction. The building is flexibilized (its fundamental period is dramatically elongated), thus being essentially uncoupled from the horizontal ground motion; therefore, the design base shear force is markedly reduced. Another relevant advantage is that, since most of strain is concentrated in the isolation layer, the incorporation of additional damping is highly feasible. Base isolation has been deeply investigated, and many applications have been reported. Noticeably, a number of isolated buildings have performed satisfactorily under strong earthquakes [1–4], thus confirming entirely the efficiency of this solution.

Table 1 displays the number of buildings with base isolation in the countries where this technology is most spread; these figures are only approximated and were reported between 2013 and 2015 [5,6]. Table 1 shows that the degree of use of this technology is highly uneven, despite the high seismicity of all the considered countries. This might be due, among other reasons, to differences in the design codes.

Table 1. Number of buildings with base isolation

Country	Japan	China	Russia	Italy	USA	Chile	New Zealand	Thailand	Canada	Armenia	Turkey	Mexico	Colombia	Peru
No.	8000	4050	600	400	250	75	50	50	50	45	40	25	20	10

Some countries (Japan, China, Italy, USA, Chile, and Mexico) have their own regulations for seismic isolation. These codes differ significantly [7,8] in crucial issues such as definition of seismic hazard level, design and analysis methodologies, required performance, among others. These issues generate relevant differences in the cost of implementation of this technology. Other countries (Colombia, Peru, etc.) recommend using US regulations, not being completely fitted to local conditions. Moreover US guidelines might be over-conservative, thus discouraging the use of this solution. This work compares the codes for base isolation of Japan [9], China [10], Italy [11], USA [12,13] and Chile [14]. Remarkably, in the US, both the current [12] and forthcoming [13] regulations are analyzed. Design of seismic isolation for a RC building following these regulations is compared.

2. Review of base isolation regulations

2.1 Analysis and design procedures

For base isolated buildings, general analysis and design methodologies are considered, although with specific requirements.

Static linear analysis. This approach can be considered, provided that some conditions are fulfilled. Building height is limited to 20 m (Chile and USA ASCE 7-10), 40 m (Japan) and 60 m (China). There is no height limitation in the new American code. Japanese and Chinese codes state that isolators are located in the base of the building. In common practice, this methodology is mainly used for preliminary design.

Modal spectral analysis. Requirements for this approach are less strict. Conversely to the previous approach, design spectrum corresponds to damping 2% for short periods (corresponding to modes involving structural deformation, where linear behavior is sought) and to significantly higher damping ratios for long periods (rigid-body modes involving basically deformation in the isolation layer).

Nonlinear time-history analysis. Commonly, nonlinear behavior is concentrated in the isolator units, while the superstructure and the substructure are assumed to remain elastic. All the codes oblige to consider a number of pairs of accelerograms (acting simultaneously); this number is three in the Chilean, Chinese and former US codes, six in Japan, three to seven in Italy, and seven in the new US code. This approach is widely used in Japan and China [15,16]. In the Chilean and US regulations, the base shear from the static linear analysis can be only slightly reduced using nonlinear time-history analysis; this prescription can be over-conservative.

2.2 Seismic hazard level

2.2.1 Japan

There are two levels. Level 1 is damage limit state corresponding to probability of exceedance 63% in 50 years (T_R = 50 years); level 2 is life safety limit state and corresponds to probability of exceedance 9.5% in 50 years (T_R = 500 years). Additionally, level 3 (50% increment from level 2) is utilized for checking displacement capacity of isolation system [17]. Drift limit (Δ_{lim}, level 1) in the superstructure, is 1/200 for $H < 13$ m and 1/300 for $H \geq 13$ m (H: building height).

2.2.2 China

There are two levels. First level corresponds to frequent event with probability of exceedance 63% in 50 years (T_R = 50 years); only slight damage is accepted. Second level corresponds to maximum event with probability of exceedance 2-3% in 50 years (T_R = 1600-2500 years); no life threatening is accepted. For both levels, drift limits in superstructure (Δ_{lim}) are displayed in Table 2.

Table 2. Drift limits in superstructure (Δ_{lim}) in the Chinese code

Type of structure	Frequent Earthquake	Maximum Earthquake
Concrete frame	1/550	1/50
Concrete frame with structural walls	1/800	1/100
Tube in tube	1/1000	1/120
Steel structures	1/300	1/50

2.2.3 Italy

There are four limit states. First two correspond to serviceability conditions: Operability (SLO, 81% probability of exceedance in reference period V_R) and Damage (SLD, 63% prob.). Remaining two are ultimate: Life Safety (SLV, 10% prob.) and Collapse Prevention (SLC, 5% prob.). V_R is estimated according nominal life V_N (Table 3) and use coefficient C_U (subsection 2.4):

$$V_R = V_N\, C_U \tag{1}$$

Table 3. Nominal structural life in the Italian code

Type of construction		Nominal life (years)
1	Provisional operation. Structures under construction	≤ 10
2	Ordinary operation, bridges, dams and infrastructure constructions of limited size or normal importance	≥ 50
3	Large constructions, bridges, dams and infrastructure constructions of limited size or normal strategic importance	≥ 100

SLD. For substructure and foundations this state is fulfilled when SLV is. For superstructure, drift limit is 2/3 of the one for fixed-base buildings; in buildings with brittle partitions that are rigidly connected to the structure this limit is 0.5% of story height, otherwise 1%. In unreinforced/reinforced masonry buildings, drift limit is 0.3/0.4%.
SLV / SLC. Safety of superstructure / isolation system.

2.2.4 USA

ASCE 7-10 defines two levels. First level is Design Basic Earthquake (DBE), 10% probability to be exceed in 50 years (T_R = 475 years); is considered for designing the superstructure. Second level is Maximum Considered Earthquake (MCE), 2% probability to be exceed in 50 years (T_R = 2475 years); is considered for designing the isolation system. FEMA P-1050-1 only considers one level (MCE) for design the superstructure and the isolation system. Drift limit (Δ_{lim}) for linear / nonlinear analysis is 1.5 / 2%.

2.2.5 Chile

There are two levels, similar to those in the US code. Main difference is that the highest level (Maximum Possible Earthquake, SMP) has 5% probability to be exceed in 50 years (T_R = 950 years). Drift limit in the superstructure is 0.2%; it incorporates the response modification factor (Table 14).

2.2.6 Summary

Table 4 presents a summary of the hazard level requirements.

Table 4. Return period of the design input (years)

Country	Superstructure	Isolation system
Japan	500	500
China	1600 – 2500	1600 – 2500
Italy	475 – 950	975 – 1950
USA (ASCE 7-10)	475	2475
USA (FEMA P-1050-1)	2475	2475
Chile	475	950

Remarkably, using the static linear analysis, only US and Chilean codes permit tension in the isolators.

2.3 Soil classification and site effects

Regarding this issue, there is no difference with prescriptions for fixed-base buildings.

2.4 Importance factor

Italian code proposes coefficients equal to those for fixed-base buildings: C_U = 0.7/1/1.5/2 for class I/II/III/IV, respectively. China code does not include any factor and the others take it equal to 1, regardless of the actual importance. In Japan is customary to consider 1.25 in public buildings and 1.5 in essential facilities [18].

2.5 Response reduction factor due to damping

Since base isolation permits important damping increases, this issue is relevant. Expressions for each country follow.

Japan $$F_h = \frac{1.5}{1 + 10\,(h_{\mathrm{v}} + 0.8\,h_{\mathrm{d}})} \geq 0.4 \tag{2}$$

h_{v} and h_{d} are viscous and hysteretic damping factors, respectively. For 5% damping, $h_{\mathrm{v}} + 0.8\,h_{\mathrm{d}} = 0.05$.

China $$\gamma = 0.9 + \frac{0.05 - \xi}{0.3 + 6\,\xi} \qquad \eta_1 = 0.02 + \frac{0.05 - \xi}{4 + 32\,\xi} \geq 0.0 \qquad \eta_2 = 1 + \frac{0.05 - \xi}{0.08 + 1.6\,\xi} \geq 0.55 \tag{3}$$

In these expressions ξ is damping factor; use of γ, η_1 and η_2 is described in equation (9).

Italy $$\eta = \left(\frac{10}{5 + 100\,\xi}\right)^{1/2} \geq 0.55 \tag{4}$$

USA $$\frac{1}{B} = 0.25(1 - \ln \xi) \tag{5}$$

Chile $$\frac{1}{B_{\mathrm{D}}} = B_0 - (B_0 - 1)\exp(-a\,T_D\,|\beta - 0.05|) \qquad B_0 = \frac{2\,(1 + \beta)}{1 + 14.68\,\beta^{0.865}} \tag{6}$$

In equation (6), T_{D} is soil period, β is damping factor and values of coefficient a are listed in (Table 5). Alternatively to equation (6), equation (5) can be used (this is a more conservative approach).

Table 5. Coefficient a in the Chilean code

β	Soil I	Soil II	Soil III
0.10	396.9	293.1	224.5
0.15	180.7	124.6	98
0.20	117.9	76.1	57.1
0.25	94.0	54.3	39.6
0.50	36.9	22.2	16.1

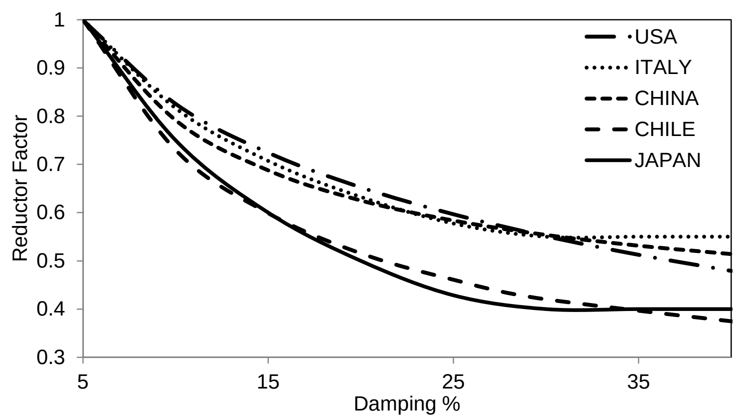


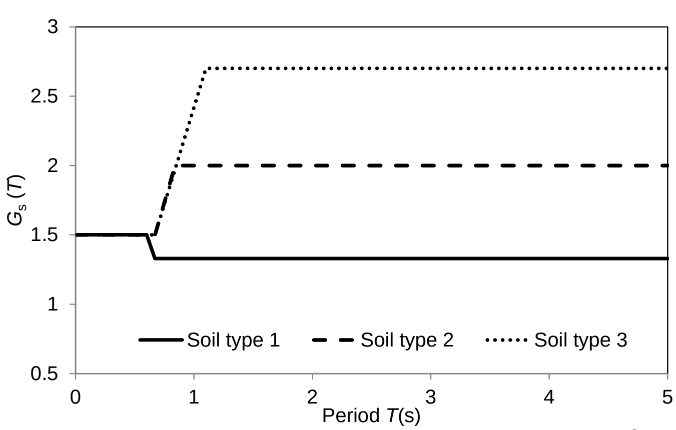
Figure 1. Reduction factor due to damping

Figure 1 displays the response reduction factor due to damping for any country; for China, η_2 is plotted. Figure 1 shows that factors for Japan and Chile are significantly smaller than the others.

2.6 Design spectra

2.6.1 Japan

Spectral acceleration S_{a} is given for equation (7). Z is zone factor (ranging between 0.7 and 1), $G_{\mathrm{s}}(T)$ is the soil amplification factor (Figure 2) and S_0 is the spectral acceleration in the bedrock (equation (8)). In equation (8), left / right expressions of S_0 correspond to Levels 1 / 2, respectively.



$$S_{\mathrm{a}} = Z\,G_{\mathrm{s}}(T)\,S_0(T) \tag{7}$$

Figure 2. G_s Factor (Japan)

$$\begin{array}{ccc} S_0 = 0.64 + 6\,T & S_0 = 3.2 + 30\,T & T < 0.16 \\ S_0 = 1.6 & S_0 = 8.0 & 0.16 \leq T < 0.64 \\ S_0 = 1.024\,/\,T & S_0 = 5.12\,/\,T & 0.64 \leq T \end{array} \qquad (8)$$

2.6.2 China

Design spectrum obeys to equation (9), where η_1, η_2 and γ depend on damping factor (equation (3)), T_g is the soil characteristic period and α_{max} is a factor related to the seismic intensity (Table 6).

$$\begin{array}{llll} S_a = 0.45\,\alpha_{max} & T = 0 & S_a = \eta_2\,\alpha_{max} & 0.1 \leq T \leq T_g \\ S_a = \left(\frac{T_g}{T}\right)^{\gamma} \eta_2\,\alpha_{max} & T_g \leq T < 5\,T_g & S_a = (\eta_2\, 0.2^{\gamma} - \eta_1\,(T - 5\,T_g))\,\alpha_{max} & 5\,T_g \leq T \leq 6 \end{array} \qquad (9)$$

Table 6. Parameter α_{max} of Chinese code

Hazard level	**Intensity**			
	6	**7**	**8**	**9**
Frequent Earthquake	0.04	0.08–0.12	0.16–0.24	0.32
Rare Earthquake	0.28	0.50–0.72	0.90–1.20	1.40
Design Earthquake	0.05	0.10–0.15	0.20–0.30	0.40

2.6.3 Italy

Design spectrum is given by equation (10).

$$\begin{array}{llll} S_a = a_g\,S\,\eta\,F_0 \left[\frac{T}{T_B} + \frac{1}{\eta\,F_0}\left(1 - \frac{T}{T_B}\right)\right] & 0 \leq T < T_B & S_a = a_g\,S\,\eta\,F_0 & T_B \leq T < T_C \\ S_a = a_g\,S\,\eta\,F_0 \frac{T_C}{T} & T_C \leq T < T_D & S_a = a_g\,S\,\eta\,F_0 \frac{T_C\,T_D}{T^2} & T_D \leq T \end{array} \qquad (10)$$

a_g is acceleration at bedrock, $S = S_T\,S_S$ (S_T: topographic amplification, Table 7; S_S: stratigraphic amplification, Table 8), η is from equation (4), and F_0 is the maximum spectral amplification factor, depending on location. Regarding periods, $T_C = C_C\,T_C*$, $T_B = T_C\,/\,3$, and $T_D = 1\,a_g\,/\,g + 1.6$. C_C depends on soil type (Table 8) and T_C^* depends on location.

Table 7. Topographic amplification coefficient in the Italian code [11]

Topographic category	S_T	**Characteristics of the topographic surface**
T1	1.0	Flat surfaces, smooth slopes and isolated hills with average inclination i <15°
T2	1.2	Slopes with average inclination i > 15°
T3	1.2	Reliefs with crest width much lower than in the base and average inclination i, 15° ≤ i ≤ 30°
T4	1.4	Reliefs with crest width much lower than in the base and average inclination i > 30°

Table 8. Stratigraphic amplification coefficient in the Italian code [11]

Soil Type	S_s	C_c
A	1.0	1.0
B	$1.00 \leq 1.40 - 0.40\,F_o\,a_g\,/\,g \leq 1.20$	$1.10\,(T_C^*)^{-0.20}$
C	$1.00 \leq 1.70 - 0.60\,F_o\,a_g\,/\,g \leq 1.50$	$1.05\,(T_C^*)^{-0.33}$
D	$0.90 \leq 2.40 - 1.50\,F_o\,a_g\,/\,g \leq 1.80$	$1.25\,(T_C^*)^{-0.50}$
E	$1.00 \leq 2.00 - 1.10\,F_o\,a_g\,/\,g \leq 1.60$	$1.15\,(T_C^*)^{-0.40}$

2.6.4 USA

Design spectrum obeys to equation (11), where S_{DS} and S_{D1} are design acceleration for short periods and for 1 s, respectively.

$$S_{DS}(0.4 + 0.6\,T/T_0) \quad 0 \leq T < T_0 \qquad S_{DS} \quad T_0 \leq T \leq T_S \qquad S_{D1}/T \quad T_S < T \leq T_L \qquad S_{D1}\,T_L/T^2 \quad T > T_L \qquad (11)$$

In equation (11), $S_{DS} = (2/3)\, F_a\, S_S$ and $S_{D1} = (2/3)\, F_v\, S_1$, where S_S and S_1 are design accelerations (MCE) for short periods and 1 s, respectively. F_a (Table 9) and F_v (Table 10) are site coefficients.

Table 9. Site effects (USA) in the short periods range [12,13]

Soil type	***F*a**						
	$S_S \le 0.25$	$S_S = 0.5$	$S_S = 0.75$	$S_S = 1.0$	$S_S = 1.25$	$S_S > 1.25$	$S_S \ge 1.5$
A	0.8/0.8	0.8/0.8	0.8/0.8	0.8/0.8	0.8/0.8	0.8/N.A	N.A/0.8
B	1.0/0.9	1.0/0.9	1.0/0.9	1.0/0.9	1.0/0.9	1.0/N.A	N.A/0.9
C	1.2/1.3	1.2/1.3	1.1/1.2	1.0/1.2	1.0/1.2	1.0/N.A	N.A/1.2
D	1.6/1.6	1.4/1.4	1.2/1.2	1.1/1.1	1.0/1.0	1.0/N.A	N.A/1.0
E	2.5/2.4	1.7/1.7	1.2/1.3	0.9/*	0.9/*	0.9/N.A	N.A/*

Table 10. Site effects (USA) in the long periods range [12,13]

Soil type	***F*v**						
	$S_1 \le 0.10$	$S_1 = 0.2$	$S_1 = 0.30$	$S_1 = 0.4$	$S_1 = 0.5$	$S_1 \ge 0.5$	$S_1 \ge 0.6$
A	0.8/0.8	0.8/0.8	0.8/0.8	0.8/0.8	N.A/0.8	0.8/N.A	N.A/0.8
B	1.0/0.8	1.0/0.8	1.0/0.8	1.0/0.8	N.A/0.8	1.0/N.A	N.A/0.8
C	1.7/1.5	1.6/1.5	1.5/1.5	1.4/1.5	N.A/1.5	1.3/N.A	N.A/1.4
D	2.4/2.4	2.0/2.2	1.8/2.0	1.6/1.9	N.A/1.8	1.5/N.A	N.A/1.7
E	3.5/4.2	3.2/3.3	2.8/2.8	2.4/2.2	N.A/2.2	2.4/N.A	N.A/2.0

Right/left values correspond to ASCE 7-10/FEMA P-1050-1. "*" means that a site response analysis is necessary. Periods $T_0 = 0.2\, S_{D1} / S_{D2}$ and $T_S = 5\, T_S$. Period T_L depends on location and is defined in [12].

2.6.5 Chile

Chile has design spectra which are specific for base isolation:

$$\begin{array}{llll} \frac{A\,(\alpha_A - 1)}{T_b - T_a}(T - T_a) + A & T_a \le T \le T_b & \alpha_A\, A & T_b < T \le T_c \\ (2\,\pi/T)\,\alpha_V\, V & T_c < T \le T_d & (2\,\pi/T)^2\,\alpha_D\, D & T > T_d \end{array} \qquad (12)$$

Required parameters are listed in Table 11. These parameters are defined for seismic zone 2, with maximum ground acceleration A = 0.4 g, 0.41 g and 0.45 g for soils I, II and III, respectively. For soil type IV, a specific site spectrum is required. For seismic zones 1 and 3, spectrum is modified with factors 0.75 and 1.25, respectively.

Table 11. Parameters for the generation of the design spectrum in Chile [14]

	Soil type		
	I	**II**	**III**
T_a (s)	0.03	0.03	0.03
T_b (s)	0.11	0.20	0.375
T_c (s)	0.29	0.54	0.68
T_d (s)	2.51	2.00	1.58
$\alpha_A\, A$ (cm/s^2)	1085	1100	1212
$\alpha_V\, V$ (cm/s)	50	94	131
$\alpha_d\, D$ (cm)	20	30	33

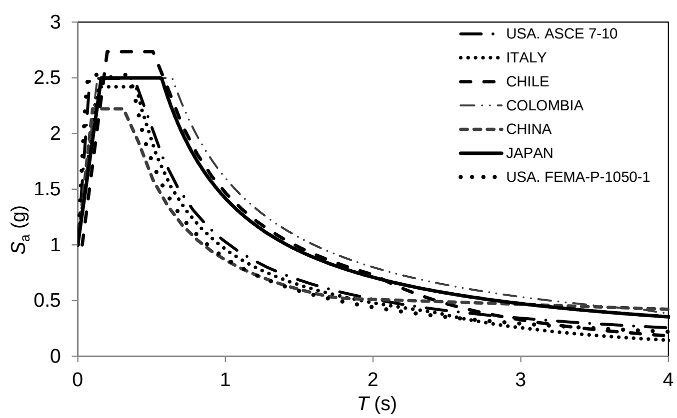


Figure 3. Design spectra for different codes

2.6.6 Comparison among design spectra

Figure 3 presents the spectra described in the previous subsections, together with the one of Colombia. Damping 5%, importance factor I = 1, response reduction factor R = 1 and soil with $v_{s,30}$ = 500 m/s (average shear wave velocity). Spectra are normalized with respect to zero period ordinate. Figure 3 shows that, for the range of periods of interest for isolated buildings (2 – 3 s), spectra for Colombia and Japan have the highest ordinates while spectra for Italy and FEMA P-1050-1 have the lowest.

2.7 Design displacements and forces

This subsection discusses the prescriptions for design displacements of isolators (D), design forces for substructure (F_{sub}), design forces for superstructure (F_{sup}), and forces for obtaining drift limit (F_{Δ}). Drift limit (Δ_{lim}) is described in subsection 2.2. Table 12 summarizes values of D_D and F_{sup} (as a base shear above the isolation system).

Table 12. Design displacements and forces

Country	Design displacements for isolators (D)	Design forces for the superstructure (F_{sup})
Japan	$1.2\ M\ F_h\ S_a/K_e$	$1.3\ D\ K_e$
China	$S_a\ \beta\ M/K_e$	$0.85\ S_a\ \beta\ M$
Italy	$S_a\ M/K_{esi\ min}$	$S_a\ M/R$
USA (ASCE 7-10)	$g\ S_{D1}\ T_D/4\ \pi^2 B$	$D\ K_{e\ max}/R$
USA (FEMA-P-1050-1)	$g\ S_{M1}\ T_M/4\ \pi^2 B$	$K_M \frac{D}{R}\left(\frac{W_s}{W}\right)^{1-2.5\ \beta}$
Chile	C_D/B_D	$D\ K_{e\ max}/R$

Regarding Japan and China, M is mass, F_h obeys equation (2) and K_e is effective stiffness. By assimilating the dynamic behavior of isolated building to a SDOF, K_e is obtained as

$$K_e = \frac{4\ \pi^2\ M}{T^2} \tag{13}$$

Reduction factor β for China is obtained after ratios between base shear for isolated and fixed-base building, Table 13.

Table 13. β factor (Chinese code) in terms of ratio between base shear [10]

Ratio	0.53	0.35	0.26	0.18
β factor	0.75	0.50	0.38	0.25

Table 13 shows that the minimum reduction factor is 0.25; however, the force for the isolated building cannot be lower than the one of a fixed-base building under a seism with intensity 6 [19]. In Japan and China there is no any response modification factor due to ductility; it is represented indirectly for drift limits. In the rest of the countries this factor is represented by R, Table 14.

Table 14. Response modification factor

Country	R
Italy	1/1.5 for serviceability conditions/ultimate limit state
USA	$1 \leq 3/8\ R \leq 2$ (R: factor for fixed-base buildings)
Chile	2 for any structure, except 1.6 for eccentric bracing and 1.4 for cantilever

Table 14 shows that elastic / near elastic behavior is expected for serviceability / design conditions. In most codes, design forces for the substructure (F_{sub}) are obtained by multiplying those of the superstructure (F_{sup}) by R; in Chile $R \leq 1.5$.

Regarding expressions in Table 12 for Italy and the US, $K_{esi,min}$ and $K_{e,max}$ correspond, respectively, to minimum and maximum equivalent stiffness with respect to variability of mechanic parameters of isolators. K_M is the equivalent stiffness corresponding to the maximum displacement (MCE). W/W_s are effective seismic weights with/without the base level weight. T_D is the fundamental period of the isolated building. USA code assumes that 1 second corresponds always to the constant velocity branch of spectrum; this consideration might not be valid for Colombia and other countries.

Regarding expressions in Table 12 for Chile, remarkably, D and F_{sup} are independent of fundamental period of the isolated structure; this relies on the consideration that, in this range of periods, spectrum is near flat. C_D for SMP depends on soil and seismic zone: soil I, II, III, C_D = 240 Z, 360 Z, 396 Z. In zones 1, 2, 3, Z = 3/4, 1, 5/4.

In Japan, Italy and Chile, F_{sup} is distributed almost uniformly among stories. China and USA propose approximately triangular distribution.

Regarding forces for obtaining drift limit (F_Δ), in China and Chile codes $F_\Delta = F_{sup}$. In Japan and Italy, F_Δ corresponds to Level 1 and SLD, respectively. In USA, $F_\Delta = F_{sup}\, R$.

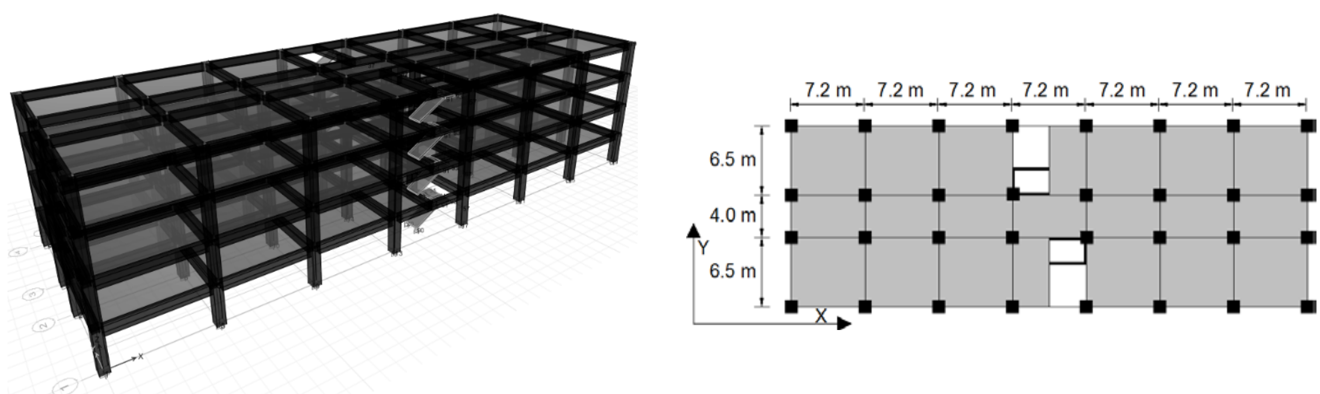
Some calculations require obtaining seismic accelerations for return periods different from the reference one; this operation can be done through modification factor $(475/T_R)^{0.3}$ [20].

3. Example of a sanitary building

3.1 General considerations

A RC sanitary prototype building located in Villavicencio (high seismicity zone of Colombia) is analyzed. Initially, building is designed as fixed-base according to Colombian design code [21]; then the isolated building is designed according to US regulations, as indicated in the Colombian code. For the sake of comparison, the design parameters are compared with those for Japan, China, Italy and Chile; this comparison is carried out for the same target fundamental period and damping. Since Italian code allows considering different importance factors, housing use is also considered.

3.2 Prototype building



(a) 3D view (b) Plan view

Figure 4. Prototype building

The prototype building (Figure 4) is based on the recommendations of the Colombian Ministry of Social Protection [22]. Main characteristics are: (i) moderate height, (ii) horizontal architecture model, aiming to facilitate access and circulation, (iii) large span-length, for better flexibility of use, (iv) many vertical connections (stairs, elevators, ramps), (v) many horizontal connections (e.g. corridors) inside each story. Figure 4 shows that the considered building has four stories and one basement; story height is 3 m. Structure is a 3-D RC frame. Dead load is 7 kN/m^2 for floors and 4 kN/m^2 for roof; live load is 4 kN/m^2 for surgery rooms and laboratories, 2 kN/m^2 for rooms and 5 kN/m^2 for stairs, corridors and other public areas. Seismic weight for the fixed-base building is 35021 kN (D + 0.3 L). Soil type is C [12]. Main parameters for seismic design are: damping 5%, A_a = 0.35, A_v = 0.30, F_a = 1.05, F_v = 1.5, T_0 = 0.122 s, T_C = 0.588 s, T_L = 3.60 s, I = 1.5, $R = \phi_a\ \phi_p\ \phi_r\ R_0 = 1 \times 1 \times 1 \times 7 = 7$, Ω_0 = 3 (moment-resistant frames with especial energy dissipation capacity, DES), maximum drift 0.01. Table 15 displays periods and modal masses in each direction for first three modes. Table 15 shows that stiffness is rather similar in both directions, and that building is not completely symmetric, since in first two *x/y* modes the "transverse" *y/x* mass is not negligible.

Table 15. Modal parameters of the fixed-base building

Mode	Period (s)	Modal mass (*x*)	Modal (*y*)	Rotational mass
1	0.513	0.8152	0.0045	0
2	0.470	0.0046	0.8156	0
3	0.449	0	0	0.8216

3.3 Isolation system

Isolators are rubber bearings (NRB) and rubber bearings with lead core (LRB); viscous dampers are also incorporated. Both types of devices are installed in the top of basement columns. Target values for fundamental period and damping are 2.80 s and 25%, respectively.

3.4 Design of the building and the isolation system in Colombia with the current American code

Drift limit for superstructure (subsection 2.2.4) for T_R = 475 years is 0.015 × 3 = 4.5 cm. Reduction factor due to damping (equation (5)) is $1 / B = 0.25(1 - \ln \xi) = 0.597$. Spectral ordinate is obtained after Colombian code [21] (subsection 3.2): S_a = 0.19 g. I = 1, $R = \phi_a \phi_p \phi_r R_0$ = 1 × 1 × 1 × 2 = 2. Effective stiffness from equation (13): K_e = 17977 kN/m; $K_{e,max}$ = 1.3 K_e [23]. Main design results are displacement D (Table 12), force F_{sub} (subsection 2.7), force F_{sup} (Table 12), force F_{Δ} (subsection 2.7) and drift limit Δ_{lim} (subsection 2.2). These results are displayed in Table 19 and Table 20 (for USA). Table 16 displays mechanic and geometric parameters of isolators. Figure 5 depicts their distribution.

Table 16. Characteristics of the isolators

Property	Type of isolator	
	Natural rubber	**Lead rubber**
Diameter (mm)	600	600
Thickness of each rubber layer (mm)	5	6
Total rubber height (mm)	215	230
Diameter of lead core (mm)	-	90
Shear modulus of rubber (MPa)	0.392	0.385
Elastic stiffness (kN/m)	515	619
Yield force (kN)	-	54.91
Plastic stiffness (kN/m)	-	476
Effective stiffness for design displacement (kN/m)	515	715
Effective damping (%)	-	20.38

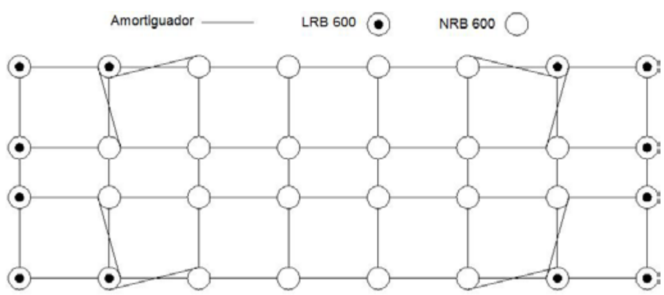


Figure 5. Distribution of isolators and dampers

Table 17 displays periods and modal masses in each direction for first six modes of the isolated building; obviously, first three modes correspond to deformation of isolators and next three to superstructure deformation [24]. Values for first three modes show that stiffness in both directions is almost alike and that behavior is completely symmetric. Comparison among modes 4 to 6 with Table 15, shows that periods have shortened and that modal shapes are similar [24].

Table 17. Modal parameters of the isolated building

Mode	Period (s)	Modal mass (x)	Modal (y)	Rotational mass
1	2.812	0.9994	0	0
2	2.803	0	0.9995	0
3	2.471	0	0	0.9994
4	0.301	0.0005	0	0
5	0.290	0	0.0004	0
6	0.268	0	0	0.0005

3.5 Design parameters with others codes

Reduction factor due to damping for each country (Figure 1, subsection 2.5) is displayed in Table 18. Table 18, similarly to Figure 1, shows that Japan and Chile codes allow considering higher benefit of damping increase. Spectral ordinate is obtained from Colombian code [21] (S_a = 0.19 g).

Table 18. Reduction factor due to damping

Country	Factor
Japan	0.429 (F_h, equation (2))
China	γ = 0.789, η_1 = 0.0033, η_2 = 0.583 (equation (3))
Italy	0.577 (η, equation (4))
USA	0.597 (B, equation (5))
Chile	0.461 (B_D, equation (6))

Table 19 displays design forces for the superstructure (F_{sup}, Table 12) and forces for calculating drifts (F_Δ, subsection 2.7); corresponding return periods (T_R) are also displayed. Drift limits (Δ_{lim}, subapartado 2.2) are indicated as well; they refer to relative displacement between top and ground floors (above the isolation system).

Table 19. Design force and drift for the superstructure

Country	Force		Drift			
	T_R (years)	Design force F_{sup} (kN)	T_R (years)	Force F_Δ for calculating drift (kN)	Drift limit Δ_{lim} (mm)	F_Δ / Δ_{lim} (kN/mm)
Japan	500	4533	50	2272	60	37.87
China	2000	7423	2000	7423	240	30.93
Italy (hospital)	950	3168	100	2418	40	60.45
Italy (housing)	475	2573	50	1964	40	49.10
USA (ASCE 7-10)	475	3748	475	5623	180	31.23
USA (FEMA P-1050-1)	2475	4731	2475	7097	180	39.43
Chile	475	2484	475	2484	24	103.5

Table 19 provides the following remarks:

- Design forces are highest in China and in the new US code and smallest in the Chilean one.
- To compare design forces for the superstructure corresponding to same return period (500 years), modification factor $(500/T_R)^{0.3}$ is considered [20]. Results are: 4897 kN (China), 2613 kN (Italy), 3806 kN (USA ASCE 7-10), 2928 (USA FEMA P-105-1) and 2522 kN (Chile). Highest demand corresponds to China and lowest to Chile and Italy; differences are relevant.
- Ratio between force and the corresponding drift limit, ranges between 30.93 kN/mm for China and 103.5 kN/mm for Chile; obviously, differences are important. This ratio refers to the required stiffness under serviceability conditions.
- In the Italian code, differences between housing and sanitary use are significant, both for design forces and drift limits.

Table 20 displays, for the isolation system, design displacements (D_D, Table 12) and design forces (F_{sub}, subsection 2.7). The corresponding return period (T_R) is also displayed.

Table 20. Design displacement and force for the substructure

Country	T_R (years)	Design displacement D_D for the isolation system (cm)	Design force F_{sub} for the substructure (kN)
Japan	500	19.39	4533
China	2000	48.60	7423
Italy (hospital)	1950	32.80	4751
Italy (housing)	975	26.64	3859
USA (ASCE 7-10)	2475	39.48	5623
USA (FEMA P-1050-1)	2475	36.44	7097
Chile	950	25.51	2548

Table 20 provides following remarks:

- Requirements for D_D are highly uneven; China and USA values double Japanese one.
- Requirements for F_{sub} are also highly uneven, ranging between 2548 kN for Chile and 7423 for China.
- To compare design displacements corresponding to same return period (500 years), modification factor $(500/T_R)^{0.3}$ is considered [20]. Results are: 32 cm (China), 22 cm (Italy), 24 (new US), 23 cm (former US) and 21 cm

(Chile). Therefore, design displacements corresponding to the same return period are more similar than absolute ones.

4. Conclusions

The final objective of this research is to promote a design code for base isolation in Colombia. With this aim, this paper compares the codes of Japan, China, Italy, USA and Chile. These countries have been chosen because of the similarities with the Colombian situation, the levels of use of this technology, and the relevance of their regulations. For the sake of comparison, a prototype hospital building located in Villavicencio (Colombia) is designed with these regulations and with the Colombian code.

Two types of conclusions are issued: general (e.g. applicable to any building) and particular (e.g. applicable to the prototype sanitary building). General conclusions:

- **Seismic hazard**. The return period for designing the superstructure ranges between 475 (Japan, former US and Chile) and 2500 (China and new US). Regarding isolators, it ranges between 500 (Japan) and 2500 (China and USA).
- **Importance factor**. Italian code proposes coefficients equal to those for fixed-base buildings. In the other codes, it is equal to one.
- **Reduction factor due to damping**. Factors for Japan and Chile are significantly smaller than the other ones.
- **Design spectra**. For the range of periods of interest for isolated buildings, spectra for Colombia and Japan have the highest ordinates while spectra for Italy and new US code have the lowest.
- **Reduction factor due to ductility**. *R* factor in Italy is 1/1.5 for serviceability conditions/ultimate limit state, in the US code cannot exceed 2, and in Chile is 2.
- **Design forces**. In the Chilean and US regulations, the base shear from simplified analysis can be only slightly reduced using nonlinear time-history analysis.

Particular conclusions for the prototype sanitary building:

- **Superstructure**. Design forces are highest in China and in the new US code and smallest in the Chilean one. However, regarding design forces for the same return period, differences are less relevant (highest demand corresponds to China and lowest to Chile and Italy). Differences in the required stiffness under serviceability conditions are extremely important; Chile value is more than three times higher than the China one. In the Italian code, differences between housing and sanitary use are significant, both in terms of design forces and drift limits.
- **Isolation system**. Requirements are highly uneven; China and USA values double Japanese one. However, design displacements corresponding to the same return period are more similar.
- **Substructure**. Requirements are extremely unbalanced, being most demanding for China and USA and least for Chile. Noticeably, new US regulations are still more conservative.

Obtained results highlight important discrepancies among the compared codes. Current situation in Colombia (e.g. use of American regulations for designing base-isolated buildings) might not be the most desirable condition for promoting this technology.

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